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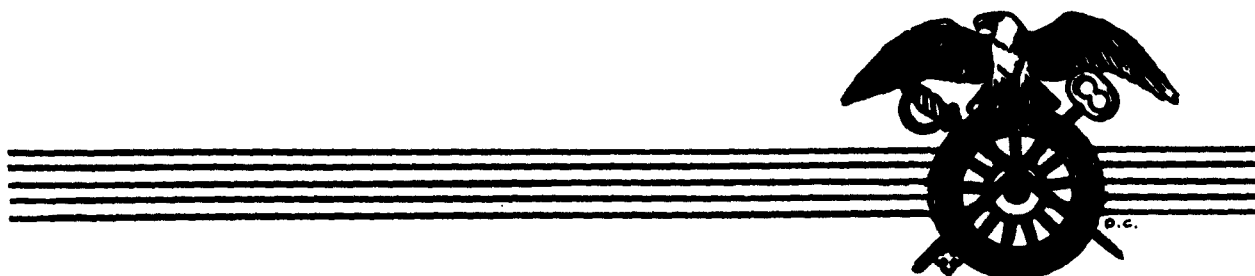
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RESEARCH AND DEVELOPMENT REPORT

TEXTILE SERIES - REPORT NO. 83

END-USE REQUIREMENTS  
VS.  
MATERIAL PROPERTIES OF TEXTILES

by  
R. G. Stoll



DEPARTMENT OF THE ARMY  
OFFICE OF THE QUARTERMASTER GENERAL

## FOREWORD

As a consumer of textiles the Quartermaster Corps has a major interest in understanding the contribution made by the properties of materials to the performance characteristics of end items. Although much Quartermaster research is concerned with the investigation of fibers and yarns as textile components, its ultimate objective is not simply to study their properties in a general sense, but to relate these properties to end-item performance.

This report by Dr. R. G. Stoll, which had been begun prior to his coming with the Quartermaster Research and Development Laboratories at Philadelphia, was developed during the course of his work with that group. In large part it represents a consolidation of Dr. Stoll's thinking based on his extensive experience in this field and of our own approach developed over the years in our day-to day-contact with the military requirements of textiles.

We believe that analyses of this type will be useful to all students of the problem of developing better textile products for consumers and to those who seek to translate the properties of fibers and yarns into end products of more satisfactory performance.

July 1953

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### Abstract

This paper presents an analysis and classification of the varied and complex end-use requirements for all types of textile structures and a summarization of a large body of information on fiber properties and their propagation into yarns and fabrics which has come to light in many studies on this subject especially in recent years. The discussions in general are on a broad qualitative basis, although they include some semiquantitative expressions of value in determining fiber, yarn, and fabric quality. The paper concludes with an analysis of the properties needed to meet the specific requirements of an important group of apparel fabrics.

## 1. INTRODUCTION

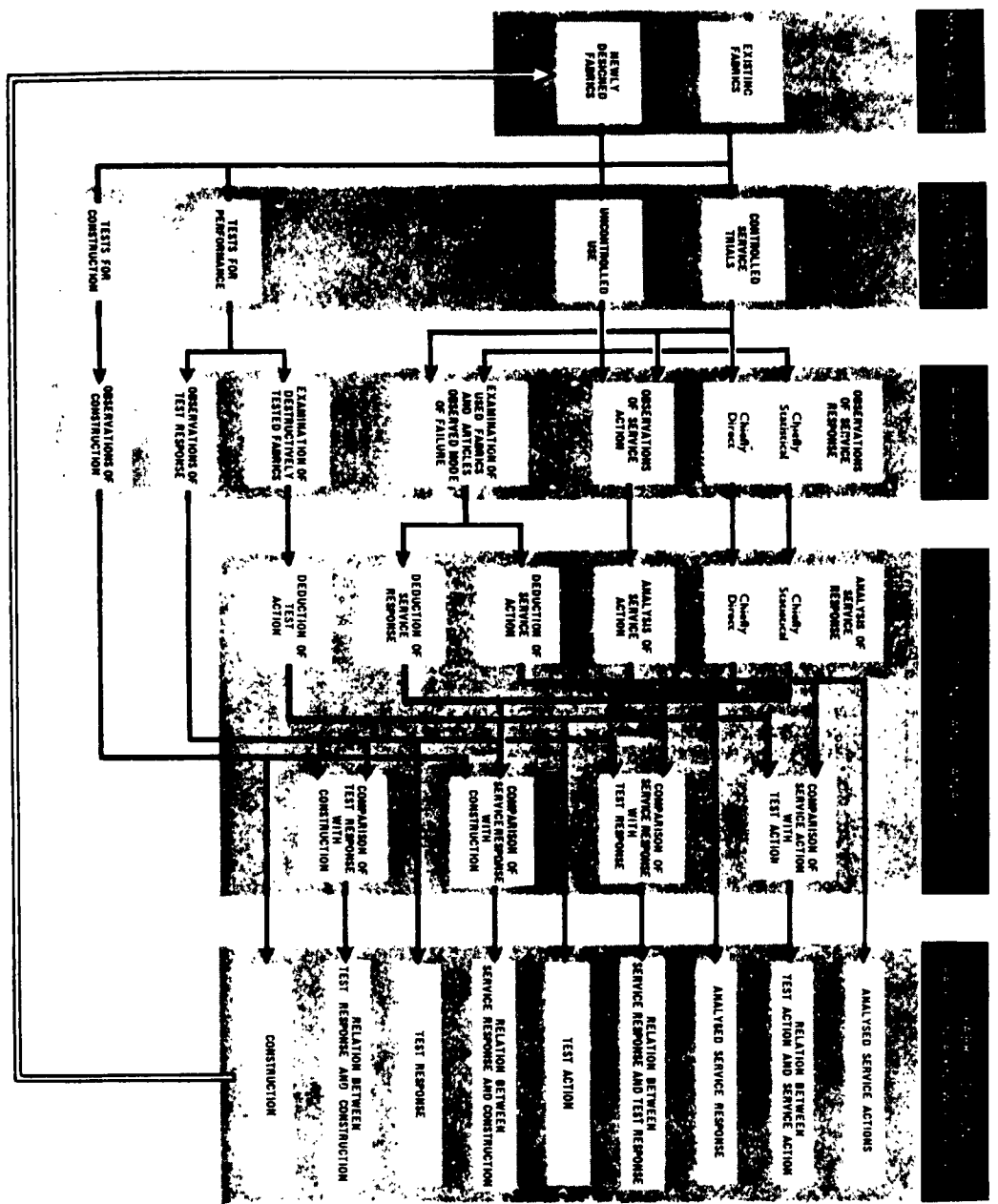
Textile materials such as woven, knitted and braided fabrics, as well as felt, are distinguished from other materials such as plastic films, rubber sheeting, and metallic foil by a unique combination of inherent material properties and a most complicated morphology or macrostructure. In other words, the complex interactions of fiber properties and fiber, yarn, and fabric geometry are responsible for the behavior of textile materials and their extraordinary capacity to meet a multitude of often conflicting end-use requirements. To discuss the quality of textile materials in the light of end-use requirements and to outline the interrelationship with the fiber properties is the purpose of this paper.

Ashcroft,<sup>(1)</sup> Buck,<sup>(6)</sup> Hamburger,<sup>(13)</sup> Hoffmann,<sup>(15)</sup> Kuenzel,<sup>(16)</sup> Smith,<sup>(25)</sup> and others in the United States; Cassie,<sup>(7)</sup> Peirce,<sup>(22)</sup> Whittaker,<sup>(28)</sup> and others in England; Boehringer, Koch, Sommer, Stoll and Weltzien<sup>(11)</sup> in Germany have concerned themselves with defining and classifying characteristics related to end-use requirements of textile materials. More recently under the research programs of the U. S. Army, Navy and Air Force, textile requirements for military purposes were studied more specifically, and valuable information was obtained on the relationship of certain service characteristics and fabric and fiber properties.<sup>(10)</sup> In connection with these studies on the quality and serviceability of textiles, the necessity of applying an engineering approach to the development of textile materials and to the utilization of fibers and finishes particularly the newer ones, was also strongly advocated. This problem which is sometimes referred to as the "blueprinting of yarn and fabric structures" was clearly outlined by Collins as shown in Figure 1.<sup>(9)</sup> According to Peirce,<sup>(22)</sup> its systematic investigation includes the following major phases:

(a) To analyze behavior in service to determine the destructive agencies, the effects they produce, and their relative importance.

(b) To determine the character of a fabric by observation of its behavior under simple, known and constant conditions; that is, to devise and apply definite tests — not complex wear tests, — but tests of structure, strength, resistance to specific kinds of abrasion or fatigue.

FIG. 1. FLOW SHEET BY COLLINS<sup>(9)</sup> SHOWING FABRIC DESIGN



(c) To correlate the measured characteristics with the effects produced by the several important and essential types of service actions.

It is not possible to discuss in detail within the confines of a short paper how much or how little our present-day knowledge has to say about this most complex problem. Instead, we intend to analyze the problem as a whole and present the various end-use requirements and fiber characteristics in an organized fashion, and discuss the factors and interactions contributing to fabric performance on a broad qualitative basis. The interaction and relative importance of some of the more important fiber properties and geometric factors will be demonstrated by some quantitative and semi-quantitative results. In summary, this will indicate that the versatility and superiority of a commercial fiber is primarily determined by a combination of many fiber properties, form factors and such complex characteristics as spinnability, weaveability, knitting quality, dyeing characteristics and adaptability to various finishing treatments, and not by only one or a few outstanding fiber properties.

## 2. END-USE REQUIREMENTS

The end-use requirements of textile materials are determined by a large number of conditions under which textile end items have to function in actual service. These service conditions may be divided into three categories: (1) end item, (2) environmental condition, and (3) customer preference. Table I gives an outline of these three categories of end-use conditions.

More than 500 end uses of textile materials, primarily fabrics, can be distinguished, even if only the major items in each of the five end-item classes are considered. Each item calls for specific requirements which, in addition, may vary considerably according to the environmental conditions under which they will be used or by desires and preferences of the individual customer. It is neither possible nor necessary in this article to list for each individual case all the major and minor requirements. Instead, a classification has been prepared which will facilitate for all kinds of textile materials the analysis of the end-use requirements and their evaluation, whether the method of testing is by laboratory techniques or field trials.

TABLE I

## THREE CATEGORIES OF CONDITIONS DETERMINING END-USE REQUIREMENTS OF TEXTILES

END ITEM	ENVIRONMENTAL CONDITIONS	CUSTOMER PREFERENCE
<u>Apparel</u> More than 50 major use groups with several hundred individual items	<u>Climatic</u> . Hot-dry (desert), hot-humid (jungle), temperate (warm to cool), wet-cold, cold-dry (artic), high altitude	Preferences and tastes of customer and individual consumer
<u>Household Textiles, Home Furnishing</u> More than 20 major use groups	<u>Biological</u> . Mold, fungus, insects	Economic and social position of consumer
<u>Medical, Surgical, Sanitary Supply</u>	<u>Mechanical</u> . Terrain, vegetation, wind, dust, sand, abrasive rocks, snagging vegetation	Special physiological and psychological requirements of individual user
<u>Military and Special Protective Textiles</u>	<u>Chemical</u> . Salt spray, smoke, smog, soot	Predispositions; allergies, idiosyncrasies
<u>Industrial and Technical Textiles</u> More than 50 major uses	<u>Sociological</u> . Tradition, economy, fashion, jurisdiction	

The end-use requirements of most fabrics and other textile products may be divided into nine major categories as shown in Table II.

TABLE II

<u>CLASSIFICATION OF END-USE REQUIREMENTS OF TEXTILE MATERIALS</u>	
1.00 Aesthetic appeal 2.00 Ease of handling 3.00 Form stability 4.00 Physiological requirements 5.00 Special functional requirements	Functional characteristics determining:  <u>Appeal</u>  <u>Suitability</u>  <u>Adaptability</u>
6.00 Retention of aesthetic appeal 7.00 Resistance to chemical degradation and disintegration 8.00 Resistance to mechanical fatigue and wear 9.00 Ultimate strength and resistance to fortuitous wear and tear	Characteristics determining:  <u>Durability</u>  <u>Wear resistance</u>

Numbers 1.00 through 5.00 represent those requirements which determine if the material has the desired appeal and the proper suitability and adaptability. Numbers 6.00 through 9.00 are concerned with the durability and wear resistance of textiles in the widest sense of the terms.

Each category can be subdivided into a large number of component characteristics, most of which in terms of physical and chemical properties are still rather complex. Table III presents this detailed and generally applicable classification of end-use requirements with a total of more than 150 individual characteristics.

The relative importance of the isolated end-use characteristics listed in this table can be accurately determined only on the basis of extensive service and laboratory tests. At present it is known only for a small number of items, principally in the industrial and military field. However, for many other end uses adequate estimates may be obtained by a qualitative analysis of the various functions.

Having defined, analyzed and classified the end-use requirements of textile materials it seems appropriate, although the subject has been sufficiently covered in the literature, to summarize briefly the fiber properties in a logical order before attempting to link them together with the fabric behavior and end-use requirements.

### 3. FIBER PROPERTIES

Under this general term only those characteristics will be considered which can be defined in terms of quantitative physical and chemical properties. The fiber properties might be divided into four categories which express the basic differences among them:

- (1) Inherent properties of the fiber material.
- (2) Geometric form (Gestalt) of the individual fibers.
- (3) Physical properties of the individual fibers.
- (4) Characteristics of bulk fibers.

Table IV lists more in detail the individual properties that can be distinguished in each category.

The inherent physical properties of the fiber material (most of which cannot be measured directly) in combination with the geometric form of the individual fibers (measurable) determine most of the fibers' physical properties. The latter characteristics (adequate test methods are available) in combination with some characteristics of the bulk fibers are responsible for the yarn-forming characteristics. In other words, the

TABLE III--CLASSIFICATION OF PROPERTIES RELATED TO END-USE REQUIREMENTS OF TEXTILE MATERIALS

A. FUNCTIONAL CHARACTERISTICS DETERMINING APPEAL - SUITABILITY - ADAPTABILITY

1.00 AESTHETIC APPEAL	2.00 EASE OF HANDLING	3.00 FORM STABILITY	4.00 PHYSIOLOGICAL REQUIREMENTS	5.00 SPECIAL FUNCTIONAL REQUIREMENTS
1.10 <u>Appearance</u> 1.11 <u>Texture</u> 1.12 <u>Color</u> 1.13 <u>Luster</u> 1.14 <u>Translucency</u>	2.10 <u>Tailoring Quality</u> 2.11 <u>Seamability</u> 2.12 <u>Resistance to allopige and fraying</u> 2.13 <u>Ease of ironing and pressing</u> 2.14 <u>Shape retention</u> 2.15 <u>Resistance to marking</u>	3.10 <u>Resistance to Shrinkage In:</u> 3.11 <u>Sponging</u> 3.12 <u>Pressing</u> 3.13 <u>Laundrying</u> 3.14 <u>Cleaning</u> 3.15 <u>Humidity</u> 3.20 <u>Crease Resistance</u> 3.21 <u>Wrinkle Recovery</u> 3.22 <u>Crease Retention</u> 3.30 <u>Stretchability (Biaxial)</u> 3.31 <u>Resistance to stretching</u> 3.32 <u>Recovery from stretching</u> 3.40 <u>Compressibility</u> 3.41 <u>Resistance to compression</u> 3.42 <u>Recovery from compression</u>	4.10 <u>Comfort Factors</u> 4.11 <u>Weight</u> 4.12 <u>Drainability</u> 4.13 <u>Touch</u> 4.14 <u>Heat transmission by:</u> 4.141 <u>Conduction-convection</u> 4.142 <u>Radiation</u> 4.143 <u>Evaporation-convection</u> 4.15 <u>Absorption</u> 4.16 <u>Air and water vapor permeability</u> 4.17 <u>Static</u> 4.18 <u>Odor and taste, inherent and effected by perspiration and wearing</u> 4.19 <u>Dermatological congruity</u> 4.20 <u>Retention of Comfort Requirements After:</u> 4.21 <u>Laundrying</u> 4.22 <u>Cleaning</u> 4.23 <u>Wearing and other service actions</u> 4.30 <u>Water Resistance</u> 4.31 <u>Absorption</u> 4.32 <u>Repellency</u> 4.33 <u>Impermeability</u>	5.10 <u>Special Environmental Requirements</u> 5.11 <u>Extreme climatic conditions</u> 5.12 <u>High altitude</u> 5.13 <u>Under water</u> 5.14 <u>Bactericidal properties</u> 5.15 <u>Insect-repellent properties</u> 5.16 <u>Proofness against gas and war chemicals</u> 5.17 <u>Protection against radiation</u> 5.18 <u>Fire resistance</u> 5.19 <u>Special camouflage characteristics</u> 5.20 <u>Suitability for Special Industrial Requirements</u> For example, adhesion with rubber, plastic coatings and synthetic resins; special degree of purity with regard to aging and catalytic action (free of metallic traces); special properties for industrial packings, as in bearings, fittings, etc; special electrical properties; special filtering properties; dust proofness, translucency; resistance to special chemical and catalytic attacks; etc. 5.40 <u>Special Properties for Medical Surgical and Sanitary Requirements</u> For example, degree of purity, capacity of absorption, surface activity, antiseptic action, therapeutic properties
1.20 <u>Hand and Drapes</u> 1.21 <u>Density-compact to open</u> 1.22 <u>Softness-soft to hard</u> 1.23 <u>Stretchability-stretchy to nonstretchy</u> 1.24 <u>Stiffness-stiff to pliable</u> 1.25 <u>Resilience-springy to limp</u> 1.26 <u>Contour-smooth to rough</u> 1.27 <u>Friction-harsh to alipery</u> 1.28 <u>Touch-warm to cold</u>	2.20 <u>Cleanliness</u> 2.21 <u>Resistance to soilage and staining</u> 2.22 <u>Ease of spot removing</u> 2.30 <u>Laundrying and Cleaning</u> 2.31 <u>Ease of washing</u> 2.32 <u>Resistance to laundrying and cleaning</u> 2.33 <u>Speed of drying</u> 2.34 <u>Ease of and resistance to ironing and pressing</u>			
1.30 <u>Odor and Taste</u>				

B. FUNCTIONAL CHARACTERISTICS DETERMINING DURABILITY - WEAR RESISTANCE

6.00 RETENTION OF AESTHETIC APPEAL	7.00 RESISTANCE TO CHEMICAL DEGRADATION AND DISINTEGRATION	8.00 RESISTANCE TO MECHANICAL FATIGUE AND WEAR	9.00 ULTIMATE STRENGTH AND RESISTANCE TO FORTUITOUS WEAR AND TEAR
<p>6.10 Fastness of Color and Bleach</p> <p>6.11 Wash fastness</p> <p>6.12 Fastness to cleaning, dry and wet</p> <p>6.13 Fastness to pressing, dry and wet</p> <p>6.14 Lightfastness</p> <p>6.15 Resistance to gas fading</p> <p>6.16 Fastness to sea water</p> <p>6.17 Fastness to perspiration</p> <p>6.18 Fastness to crocking</p> <p>6.19 Fastness to storage</p> <p>6.20 Fastness to weather</p> <p>6.30 Resistance to Spotting</p> <p>6.31 Water</p> <p>6.32 Perspiration</p> <p>6.33 Lime Soap</p> <p>6.34 Rust</p> <p>6.35 Fungi and molds</p> <p>6.36 Others</p> <p>6.40 Resistance to Mechanical Changes of Appearance</p> <p>6.41 Marking</p> <p>6.42 Glaziness in pressing</p> <p>6.43 Shine in wear</p> <p>6.44 Roughening and pilling in washing and wearing</p> <p>6.45 Deformation of weave and texture by yarn slippage and snagging and snarling</p> <p>6.50 Retention of Hand and Drape</p> <p>6.51 Laundering</p> <p>6.52 Cleaning</p> <p>6.53 Wearing</p>	<p>7.10 Laundering and Cleaning</p> <p>7.11 Chemical degradation of the fiber material with normal use of detergents</p> <p>7.12 Degradation (oxidation or reduction) as a result of too concentrated use of detergents and bleaching agents</p> <p>7.13 Catalytic degradation</p> <p>7.14 Degradation through high temperature during washing, drying and pressing</p> <p>7.15 Damage by undissolved detergents</p> <p>7.20 Resistance to Aging by Climatic Conditions</p> <p>7.21 Photochemical degradation</p> <p>7.22 Fatigue from too high, too low or markedly variable humidity</p> <p>7.23 Degradation from extreme cold or hot climate</p> <p>7.30 Resistance to Deterioration by Microorganisms</p> <p>7.31 Fungi</p> <p>7.32 Bacteria</p> <p>7.40 Resistance to Aging by Other Chemical Service Actions</p> <p>7.41 Perspiration</p> <p>7.42 Gases and vapors in the atmosphere</p> <p>7.43 Chemicals in connection with special technical and industrial uses</p> <p>7.44 Aging from presence of deleterious concomitant substances, for example, residues of acid, formation of acid by oxidation, autooxidation of oil, traces of metal, etc.</p> <p>7.50 Resistance to Chemical Disintegration</p> <p>7.51 Dissolving or hole formation by acids (in cellulose materials)</p> <p>7.52 By alkalies (keratin materials)</p> <p>7.53 By organic solvents</p> <p>7.54 By stain removers and drugs</p> <p>7.55 Damages by other dissolving chemicals</p> <p>7.60 Heat and Fire Resistance</p> <p>7.61 Degradation by heat</p> <p>7.62 Softening temperature</p> <p>7.63 Melting temperature</p> <p>7.64 Decomposition temperature</p> <p>7.65 Flammability</p> <p>7.66 Afterglow</p>	<p>8.10 Fatigue</p> <p>Fatigue = Decrease of inherent resistance to wear, form stability etc., without causing actual fiber breakdown</p> <p>Effect of:</p> <p>8.11 Stretching</p> <p>8.12 Compression</p> <p>8.13 Complex mechanical actions (flexing etc.)</p> <p>Static and Dynamic</p> <p>8.20 Moderate Wear</p> <p>8.201 Shine</p> <p>8.202 Roughening</p> <p>8.203 Pilling</p> <p>8.204 Threadbareness</p> <p>8.205 Slight fraying</p> <p>8.206 Seam failures</p> <p>8.21 Fabric against fabric abrasion</p> <p>8.22 Abrasion against smooth surfaces</p> <p>8.23 Internal abrasion by flexing, folding, stretching, compression</p> <p>8.24 Mechanical wear by normal laundering and cleaning methods</p> <p>8.30 Severe Wear</p> <p>8.301 Runs in knitted fabrics</p> <p>8.302 Fraying of edges, creases and folds</p> <p>8.303 Hole formation by continued wear on localized areas and projections</p> <p>8.304 Tears and breaks in worn areas</p> <p>8.31 Abrasion against rough and harsh surfaces</p> <p>8.32 Internal abrasion under high flexing, stretching, compression loads</p> <p>8.33 Laundering damages by excessive mechanical surface and internal abrasion</p>	<p>9.10 Breaking Strength (Static) Dry, Wet and Under Other Service Conditions</p> <p>9.11 Uniaxial tensile loading</p> <p>9.12 Biaxial tensile loading</p> <p>9.13 Multiaxial tensile loading (bursting)</p> <p>9.14 Tearing strength</p> <p>9.15 Resistance to crushing, puncture, shearing and cutting</p> <p>9.16 Seam strength</p> <p>9.17 Knot strength and strength of splices</p> <p>9.18 Adhesion resistance of coated and laminated fabrics</p> <p>9.20 Impact and Ballistic Strength Same condition as above, but at high speeds.</p> <p>9.30 Fortuitous Destruction by Complex Mechanical Service Action such as:</p> <p>9.31 Crushing of the fabrics (in washing machine, extractor, mechanical dryers, and pressing)</p> <p>9.32 Cuts, tears and other mechanical damages from rough and defective places in washing machines</p> <p>9.33 Breaking of frozen fabrics by winding and flexing</p> <p>9.40 Resistance to Chewing by Insects</p> <p>9.41 Moths and dermestids</p> <p>9.42 Household insects</p> <p>9.43 Termites</p> <p>9.44 Mice and other animals</p>

**TABLE IV**  
**CLASSIFICATION OF FIBER PROPERTIES**

Inherent Properties of the Fiber Material		Geometric Form of the Individual Fibers	Physical Properties of the Individual Fibers	Characteristics of Bulk Fibers
Chemical	Physical			
Dye affinity and retention --	Specific gravity -- Stress-strain-time behavior -- Moisture regain Water absorbency Swelling -- Resistivity Dielectric constant Dielectric strength -- Optical properties	Fiber length -- Fiber crimp contraction amplitude frequency -- Cross section area shape Moment of inertia Slenderness ratio	Tensile load-elongation-time relationship Breaking load Elongation at break Elastic recovery Stiffness Compliance Toughness Resilience -- Complex mechanical properties Knot strength Loop strength Shear strength Torque-twist relationship Resistance to and recovery from uncrimping	Compressibility Recovery from compression Apparent density -- Degree of opening -- Orientation (entanglement) Bulk fiber friction -- Foreign matter content -- Electric properties
Resistance to acids alkalies salts hydrocarbons organic compounds -- Resistance to photo-chemical degradation biological attack moths and other insects				
<u>Thermal Properties</u> Specific heat Thermal stability Softening Melting Decomposition Burning rate				

translation of the inherent physical properties of the fiber material into the individual fibers and into the bulk fibers is primarily effected by the geometric form of the individual fibers. In the more organized forms of fiber assemblies such as in sliver, roving, and yarn, additional geometric factors are introduced, and by the interlacing of the yarns in a fabric the mechanism becomes still more complicated. In spite of the many form factors the character of the individual fibers will determine to a large extent the behavior of fabrics. It is evident that the chemical properties listed in column 1 of Table IV as well as the thermal characteristics determine directly the corresponding fabric properties almost without interacting with the construction of yarns and fabrics. The geometric form of the fibers, their packing density in the yarn, and the density and thickness of the fabric may somewhat change the rate, although the degree or order of magnitude of these properties will not be affected significantly by the geometry of the fabric. In checking through the end-use requirements as shown in Table III one will note, however, that the chemical characteristics are by far outweighed by requirements which are primarily physical in nature. To analyze the factors contributing to the physical behavior of fabrics will be the object of the next section.

#### 4. FACTORS DETERMINING THE PHYSICAL BEHAVIOR OF FABRICS

The major factors contributing to the physical behavior of fabrics are schematically outlined in the flow chart shown in Figure 2 which illustrates that the overall physical behavior of fabrics is determined by the physical behavior of the yarn and the geometric form of the fabric. These two characteristics in turn are effected by the interactions of several groups of basic fiber properties and processing conditions as indicated in Figure 2 by the connecting lines. The physical behavior of yarn as indicated in this figure is thus generally determined by the physical properties of the individual fibers and the geometric form of the yarn, i. e., the orientation and packing density of the individual fibers within a yarn structure. The latter characteristics are the result of the general spinning characteristics which in turn are effected by the physical properties of the individual fibers; the characteristics of bulk fibers (fiber assemblies), such as interfiber cohesion, drawing characteristics, and cleanliness; the yarn construction (twist, yarn number); and the spinning conditions which again are composed of several major and a great many minor contributing factors.

Table V shows in detail the various individual characteristics into which the physical behavior of yarn, the bulk characteristics of fabrics, the geometric form of fabrics, and the fabric construction

FIG. 2

# MAJOR FACTORS CONTRIBUTING TO THE PHYSICAL BEHAVIOR OF FABRICS

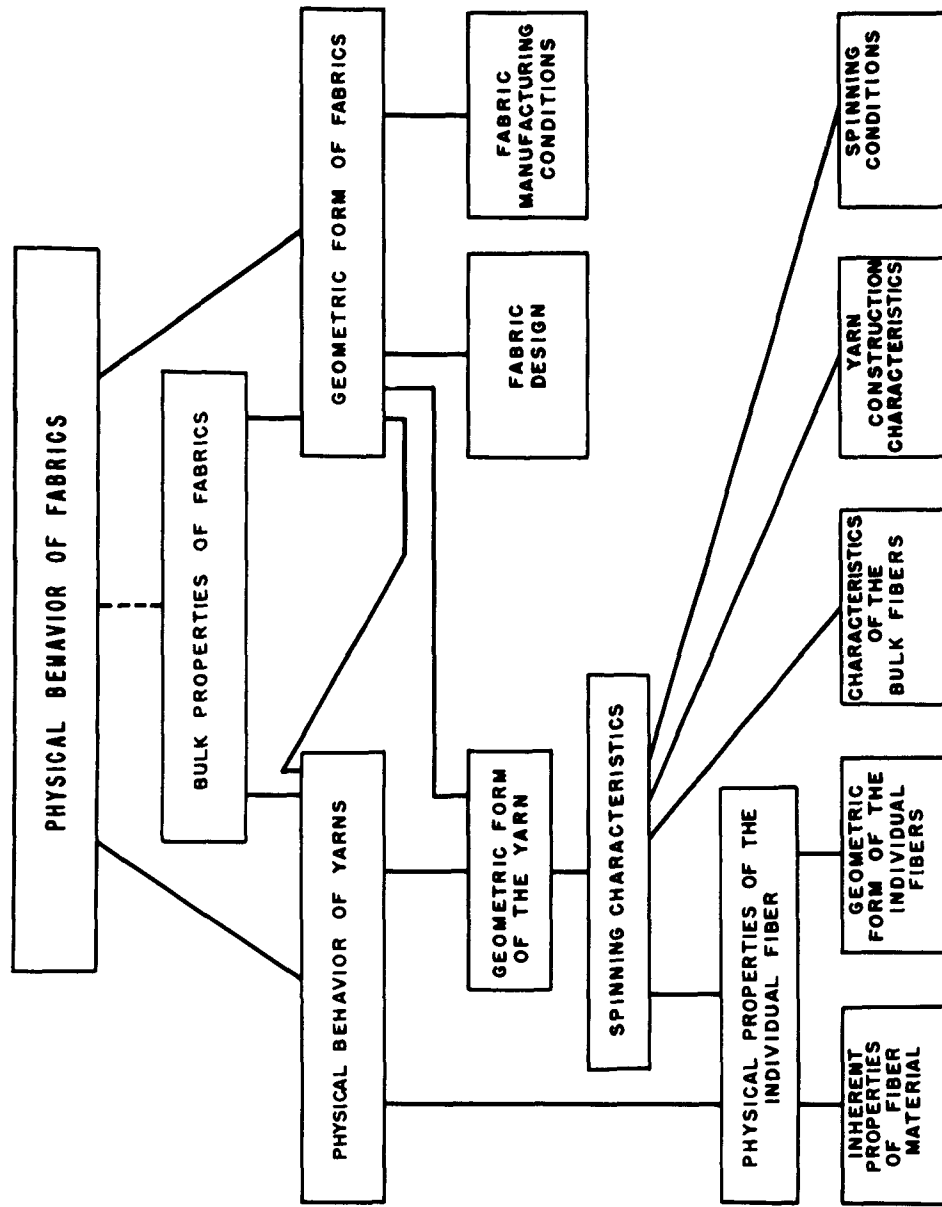


TABLE V

## CLASSIFICATION OF CHARACTERISTICS CONTRIBUTING TO THE PHYSICAL BEHAVIOR OF FABRICS

PHYSICAL BEHAVIOR OF YARNS	BULK CHARACTERISTICS OF FABRICS	GEOMETRIC FORM OF FABRICS
Axial Load-Elongation-Time Properties: Tensile strength Stiffness Toughness Elongation Elasticity Resilience	Unit weight (W) $W = 0.6857 \left[ \frac{n_1}{N_1} (1+c_1) + \frac{n_2}{N_2} (1+c_2) \right]$ $W = \frac{0.6857}{\sqrt{N_1}} [K_1 (1+c_1) + K_2 (1+c_2) \beta]$	Cover factor: warp $K_1 = n_1/\sqrt{N_1}$ filling $K_2 = n_2/\sqrt{N_2}$ weave $K = n_2(1/\sqrt{N_1} + 1/\sqrt{N_2})$
Transverse Load-Compression-Time Properties Shear strength Softness Compressibility Resilience	Thickness or volume under certain loads or pressures	Crimp (approx. equal to take-up): warp $c_1$ filling $c_2$
Complex Characteristics Knot strength Loop strength Flexibility Friction Abrasion resistance	Apparent density  Apparent density Pore volume  Total surface of the fibers per unit area	Displacement: warp $h_1$ filling $h_2$  Yarn flattening: warp filling  Repeat size  Number of interlacings per repeat and per unit area  Floating length: warp filling Projection ratio
FABRIC CONSTRUCTION CHARACTERISTICS		
<u>Yarn Count</u> Warp $(N_1)$ Filling $(N_2)$	<u>Texture</u> Ends $(n_1)$ Picks $(n_2)$ Wales Courses	<u>Take-Up</u> Warp $(c_1)$ Filling $(c_2)$  <u>Weave</u>

characteristics may be subdivided. It also indicates by equations the interactions of some of these factors. Most of these characteristics can be measured and expressed in defined physical properties. Others, particularly the parameter describing the geometric form, can be calculated as indicated in Table V.

It is not the object of this paper to discuss the contribution of yarn and fabric geometry to the physical behavior of fabrics. However, it must be mentioned that such characteristics as hand and drape (1.20), tailoring quality (2.10), resistance to shrinkage (3.10), crease resistance (3.20), stretchability (3.30), compressibility (3.40), comfort (4.10), water resistance (4.30), wear resistance (8.00) and others very often are as much or even more affected by the geometric form of yarn and fabric as by the fiber properties. For those interested in this field the basic work of F. T. Peirce<sup>(21, 23)</sup> and the more recent papers by Backer<sup>(2,3,4,5)</sup> and Painter<sup>(20)</sup> are recommended for study.

The multitude of factors contributing to yarn behavior and the complexity of the interactions involved is still better demonstrated in the qualitative analysis shown in Figure 3. This flow chart not only lists the multitude of factors and conditions contributing to the mechanical behavior of yarns, but indicates as well existing interactions. It analyzes the mechanical behavior of yarns in terms of the mechanical properties of the individual fiber (F1 through F5) and of the geometric structure of the yarn (G1 through G6). The mechanical properties of the individual fiber in turn are a function of the inherent properties of the fiber material (A1 through A9) and of the geometric form of the individual fiber (B1 through B6). The geometric structure of yarn (G) is the complex result of numerous interactions between the geometric form of the individual fiber (B), the overall spinning quality, and the yarn construction (E). Spinning quality in turn is a very complicated function of many factors which can be classified into the following four groups: geometric form of the individual fiber (B), spinning factors of bulk fibers (C), processing conditions (D), and yarn construction characteristics (E).

Each item (property, characteristic or condition) in Figure 3 is classified by the number or letter shown to the left of the item. The circles around these numbers or letters are coded as shown in the legend.

Figures 2 and 3 and Table V also indicate that the behavior of textile materials is influenced to a large extent by the manner in which the individual fibers are arranged in a yarn and the pattern in which the yarns are interlaced in a fabric. The effect of the

geometric form of yarns and fabric becomes even more evident by the following consideration. Textile structures have been characterized by Morton<sup>(19)</sup> as being somewhere between two extremes: (a) an arrangement of fibers and yarns fitting together perfectly and adhering to one another so that they possess no power of independent movement and (b) an arrangement of fibers free to move and rotate in any direction entirely independently of one another. In the former case, the yarn or fabric would behave like a monofilament or film of a given diameter or thickness, respectively. In the latter case, the structure would be that of a quasi-liquid and its behavior would be roughly the sum of the behavior of the individual fibers. In order to illustrate the effect which these two extreme limitations would exercise on the bending stiffness of a yarn of 300 denier and 100 filaments, one can show that the stiffness in case (a) would be 100 times greater than in case (b).<sup>\*</sup> A similar effect is exerted on compressibility which in combination with stiffness contributes most to such fabric characteristics as hand and drape, softness, resilience, and wrinkle resistance, as well as tear strength and wear resistance. It must be understood, of course, that practical yarn and fabric structure may approach, but can never reach, the conditions corresponding to these two extremes.

These few remarks on the importance of the morphology of yarns and fabrics together with the outline given in Table V and Figures 2 and 3 may be sufficient to demonstrate the contribution of yarn and fabric geometry to most of the physical end-use requirements of fabrics. It may be appropriate at this point to elaborate on the significance of the geometric form of the individual fiber, which plays a role equally as important as inherent material properties and yarn and fabric geometry in the propagation of fiber properties into fabric performance.

<sup>\*</sup>According to the formulae given in Table VI (page 14) for moment of inertia and stiffness of individual fibers,

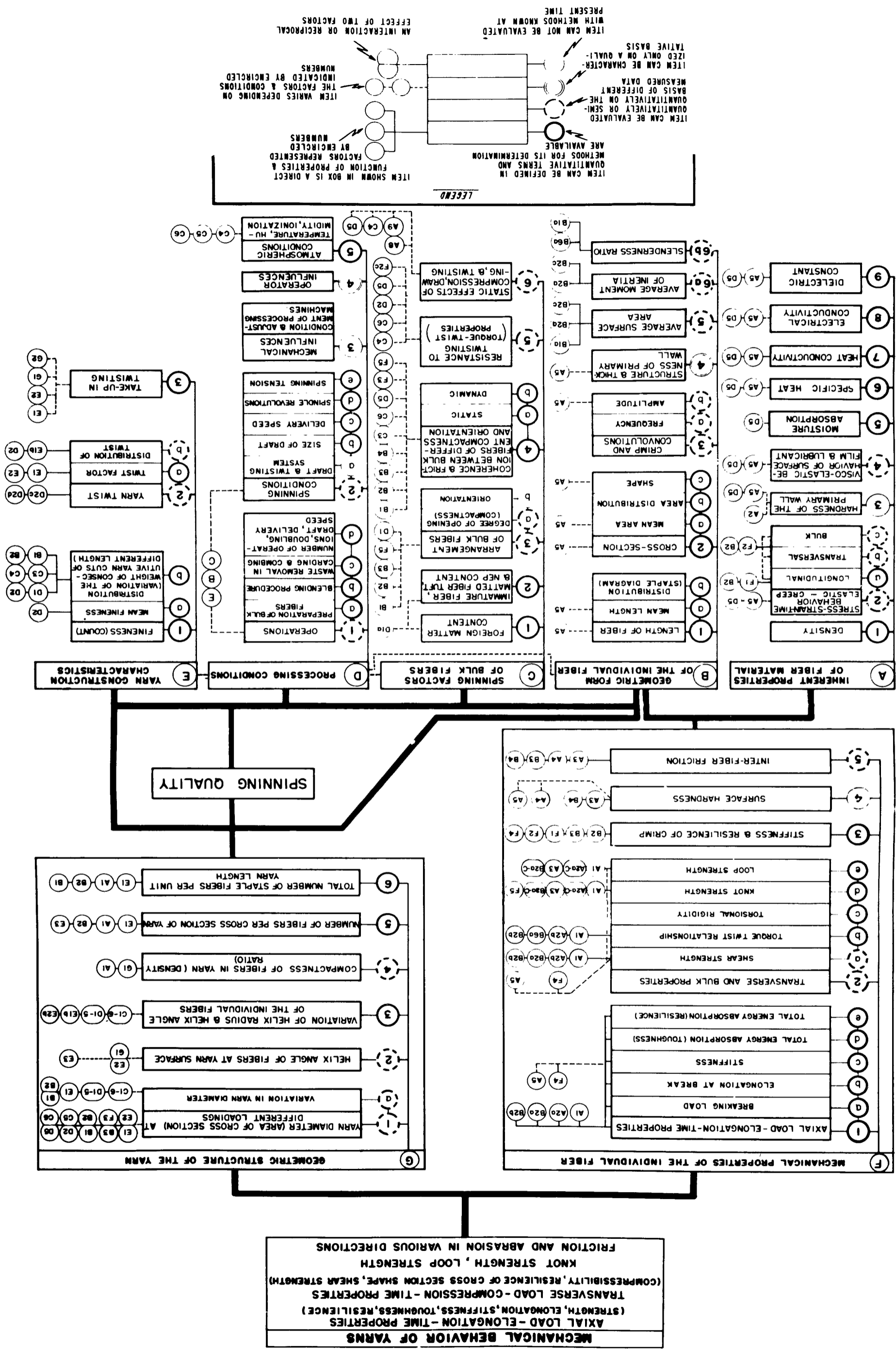
$$\text{bending stiffness of case (a), bonded yarn,} = \frac{(300)^2 \times C \times E}{(\text{density})^2 \times L}$$

$$\text{bending stiffness of case (b), yarn with} \\ \text{maximum movement of individual fibers,} = \frac{100 \times (3)^2 \times C \times E}{(\text{density})^2 \times L}$$

where C is a conversion factor, E tensional modulus of elasticity, and L the unsupported fiber length.

ANALYSIS & CLASSIFICATION OF THE FACTORS DETERMINING THE MECHANICAL BEHAVIOR OF YARNS

FIG. 3



## 5. SIGNIFICANCE OF THE GEOMETRIC FORM OF THE INDIVIDUAL FIBERS

The contribution of the geometric form of the individual fibers to the behavior of fibers, yarns, and fabrics has been indicated in Tables IV and V and Figures 2 and 3. It is now our purpose to discuss and demonstrate in greater detail the effect of the dimension and shape of the cross section of fibers on such properties as fiber surface, bending stiffness and torsional rigidity. These fiber characteristics in turn determine, to a large extent, many important end-use requirements. Cassie,<sup>(8)</sup> for example, has shown that the surface of bulk fibers, which is a function of fineness, density and cross-sectional shape, provides a drag on air movement that gives fabrics and battings their good heat insulation. A large accessible fiber surface contributes significantly to water absorption, drying speed, and water vapor transmission, and is an important factor in determining the comfort of a textile material. Smith<sup>(25)</sup> also discussed the significance of the fiber shape for the engineering of textile yarns and fabrics. He showed that the stiffness of fibers is as dependent upon their fineness as upon the inherent material and consequently that fiber fineness is a major factor in determining the hand and drape of a fabric.

Formulae and conversion factors have been derived for the quantitative consideration of the influence of the geometric character of fibers on the physical behavior of textile structures. Enough of these are shown in Table VI for the convenient calculation of fiber perimeter, fiber surface, axial and polar moment of inertia, stiffness, and torsional rigidity. The formulae are expressed in terms of easily measured fiber properties and they apply to any material, regardless of fineness or cross-sectional shape.

By comparing the actual variability of the geometric form and of the inherent properties of all major natural and man-made fibers, the data given in Table VII were obtained showing the relative importance of these characteristics with regard to stiffness and fiber surface.

Table VI  
GEOMETRICAL DATA OF TEXTILE FIBERS

CROSS SECTION	RATIO OF MAJOR DIMENSIONS (SHAPE FACTOR)	PERIMETER FACTOR	MOMENT OF INERTIA CONVERSION FACTORS		
			AXIAL (X)	AXIAL (Y)	POLAR
	1	35.5	7.96	7.96	15.92
	b/a = .637 b/a = .509 b/a = .413 b/a = .318	38.6 41.0 43.7 47.8	12.5 15.6 19.2 25.0	5.1 4.1 3.3 2.5	17.6 19.7 22.5 27.5
	b/a = 1.000 b/a = .637 b/a = .509 b/a = .413 b/a = .318	40.0 41.0 42.3 44.0 46.7	8.35 13.1 16.3 20.1 26.2	8.35 5.3 4.3 3.5 2.7	16.7 18.4 20.6 23.6 28.9
	$\frac{5a^2}{r^2 \pi} = \frac{2}{\pi} = .637$	53.7	9.65	9.65	19.3
	$\frac{a^2 \sqrt{3}}{4 r^2 \pi} = 0.413$	45.6	9.70	9.70	19.4
	$\frac{d}{r} = .637$ .509 .413 .318	45.5 49.7 54.5 62.8	17.0 23.3 30.6 42.0	17.0 23.3 30.6 42.0	34.0 46.6 61.2 84.0
	ELLIPTICAL RING OBTAINED BY DEFORMATION OF CIRCULAR RING WITH ( $\frac{d}{r}$ ) RATIO = 0.509				
	b/a = .500	51.0	36.0	11.5	47.5
	d = 0.0	52.5	127.9	6.4	134.3
	b/a ≈ 0.73 $\frac{AREA}{r^2 \pi} \approx 0.45$	53.5	41.2	18.5	59.5

PERIMETER OF INDIVIDUAL FIBERS = PERIMETER FACTOR  $\times \frac{\sqrt{GREX}}{DENSITY} \times 10^{-4}$   
(cm.)

SURFACE OF INDIVIDUAL FIBERS = PERIMETER (cm.)  $\times$  FIBER LENGTH (cm.)  
(cm<sup>2</sup>)

TOTAL SURFACE OF A MASS OF FIBERS =  $\frac{PERIMETER FACTOR \times WEIGHT OF FIBERS (g) \times 10^{-2}}{DENSITY \times GREX (OF INDIVIDUAL FIBER)}$   
(cm<sup>2</sup>)

MOMENT OF INERTIA = CONVERSION FACTOR  $\times \frac{GREX^2}{DENSITY^2} \times 10^{-14}$   
(cm<sup>4</sup>)

STIFFNESS OF INDIVIDUAL FIBERS =  $\frac{MOMENT OF INERTIA \times MODULUS OF ELASTICITY}{UNSUPPORTED FIBER LENGTH}$

TABLE VII

RELATIVE IMPORTANCE OF GEOMETRIC AND INHERENT FIBER  
PROPERTIES TO STIFFNESS AND SURFACE AREA

Characteristics of Individual Fiber	Fiber Fineness	Per Cent Relative Importance of:		
		Cross-Sectional Shape	Density	Modulus of Elasticity***
Stiffness *	87	6	1	6
	45	14	6	35
Fiber Surface**	70	24	6	—
	39	24	37	—

\*These data are based on a variation of the fiber fineness from 1 to 10 grex, which covers the majority of fibers suitable for spinning and other textile manufacturing processes. The cross-sectional variation corresponds to that shown in Table VI. The materials considered include all presently known natural and man-made fibers (except glass) as compiled in the Fiber Properties Chart of the Modern Plastics Encyclopedia, 1949 edition.

\*\*In this case Fiberglas is included but the fineness range is limited to from 1 to 5 grex, which covers the more important fiber counts used in commercial processes.

\*\*\*The relative importance of the modulus of elasticity as shown here remains essentially the same whether this property is measured by the static method or by the sonic or supersonic procedure.

The controlling effect of fineness on fiber stiffness and fiber surface, and consequently on many important service characteristics depending on these fiber properties is clearly demonstrated by the comparison given in Table VII. The cross-sectional shape of a fiber has also a significant influence on the fiber surface as shown in the table.

In the case of commercial fibers, relatively little influence on fiber stiffness is exerted by the cross-sectional shape, as has been previously expressed by Smith.<sup>(25)</sup> This is especially evident if one considers that the variation of the cross-sectional shape between different fiber samples is often not much larger than that within one sample. Although its

effect is of minor importance on fiber stiffness, the cross-sectional shape may be a major factor in yarn stiffness. It has been noticed that fibers with a ribbon or dogbone-like cross section have a tendency towards packing together when spun into yarns. This is particularly true when wet yarns or fabrics made from such fibers are dried. Under these conditions the cohesion between the fibers becomes so large that the yarn acts like a monofilament, which is very undesirable in most applications. Fibers with round cross sections and those with a permanent crimp retain enough freedom of movement in the assembly of a yarn to secure the desired softness, resilience, and flexibility.

The fiber density has very little effect on stiffness. Its effect on fiber surface is somewhat larger, particularly when Fiberglas is included in the comparison.

The modulus of elasticity or even the wide variations of the composite stress-strain-time relationship (immediate elasticity, delayed elasticity, permanent set) of all the available fibers, is of secondary importance with respect to stiffness when compared with the variations in fineness which are practical on the different spinning systems. In other words, it is relatively easy to compensate for a specific modulus by a proper selection of the fiber fineness in order to obtain the desired stiffness, flexibility and softness of the yarns and fabrics. Increasing the fiber stiffness as a result of a higher initial modulus and a coarser fiber denier has within certain limits given by the other requirements of a specific item, a favorable effect on fabric resilience and resistance to wrinkling.

Another significant correlation exists between cross-sectional shape and size and the resistance to wear. For materials with a relatively high modulus it has been found (14,27) that fibers with flat, elliptical, or hollow cross sections resist complex wear actions better than round fibers. The strains produced by fatigue, which causes a large proportion of wear, are not as high in the outer layers of flat fibers as they are in round fibers. However, owing to the detrimental effect which has been noted in some of the flat and ribbon-like fibers with regard to hand, drape and wrinkle resistance, there are definite limitations in utilizing such cross-sectional shapes independent of those given by the fiber manufacturing process. Increasing denier per filament has also been found to improve the wear life. (14,26) No adequate data are available at the present time as to where the optimum or maximum lies for different fibers and end uses. However, in most cases the limitations are set by the poorer spinnability and lower

spinning limit of the coarser fibers.

It is not the object of this paper to discuss the factors which determine the processing quality of fibers. It must be mentioned in this connection, however, that fiber fineness probably has more effect on the spinnability of staple fibers than any other fiber characteristics. Its effect is a twofold one. First, a certain number of individual fibers are required in order to secure sufficient inter-fiber cohesion and yarn evenness. Second, the fineness has a major effect on fiber stiffness and therefore creates more or less resistance to twisting, which again will affect the yarn-forming characteristics.

If practical methods of grading natural fibers are looked at from this point of view it becomes intelligible that the classifying as practiced in the marketing of natural fibers is not a mere trading quality but reflects quite well the physical behavior of these fibers. This is particularly true since in natural fibers the different geometric characteristics do not vary independently but are interrelated to the stress-strain characteristics.

This study thus demonstrates the necessity for concentrating much more than in the past on the quantitative evaluation of defined geometric fiber characteristics and their correlation to the measurable characteristics of yarns and fabrics. For the elucidation of serviceability and performance characteristics of textile materials, these studies on the effect of the geometric form of the fibers are at least as important as the investigations of the inherent material properties which have been the subject of so much interest recently.

## 6. PROPAGATION OF THE MECHANICAL FIBER PROPERTIES INTO YARNS

In Figure 2 it was indicated that the physical behavior of fabrics is determined by the interaction of the physical behavior of the yarns used in the fabric and the geometric form of the fabric, that is, the geometric form in which the yarns are interlaced in the fabric structure. Figure 3 showed that the physical behavior of the yarn again is determined by the interaction of the physical properties of the individual fibers and the geometric form of the yarn. In studying the multitude of contributing factors and conditions listed in these figures one might get the impression that the propagation of the fiber properties into yarns and fabrics becomes totally obscured by the many superimposed factors and conditions; i.e., that the inherent fiber properties may contribute only a minor portion to the behavior and that it will therefore not be possible to

predict the behavior of yarns and fabrics on the basis of the fiber properties. That this is not the case is probably best demonstrated by the fact that yarns and fabrics made from different fibers show a distinguished behavior which is associated with the inherent characteristics of the fiber material and its geometric form.

Considering tensile strength, elongation, and bursting strength of yarns and fabrics or such fabric characteristics as thickness, softness, resilience, and crease resistance, we will find that all are governed to some extent by the same or at least by closely related physical phenomena. In testing these properties an exterior force is applied to the specimen which causes displacements and deformations of the individual fibers within the fabric and yarn structure. The actions which lead gradually to a breakdown of fabrics and yarns by flexing and abrasion cause similar displacements and deformations of the individual fibers. The magnitude and duration of the exterior forces on the one hand, and the freedom of movement in the stressed portions of the individual fibers within the yarn and fabric structure in combination with the stress-strain-time behavior of the fibers on the other hand, determine the resistance of the fabrics to deformation as well as the degree of deformation which takes place in all the service or test actions mentioned as above. Consequently, the laboratory characteristics must be related to the stress-strain-time behavior of the individual fibers and to a certain extent must also be associated with each other.

The characterization of mechanical yarn properties in terms of fiber properties and parameters characterizing the geometric form of the fibers has been the object of many experimental and theoretical investigations. Matthes and Keworkian<sup>(17, 18)</sup> in a comprehensive study reviewed and supplemented the earlier studies in this field. More recently Hamburger and Platt<sup>(12, 13, 24)</sup> in their rigorous theoretical approach derived new formulae for the tensile elastic behavior of filamentous and staple yarns. Their approach is not only more elegant than the earlier ones, but the models used in their calculation appear to be more representative for the deformation mechanism in actual yarn structures. In summary the tensile elastic behavior of yarns is determined by the following three basic factors:

(a) Component Effect - Owing to the helical path of the individual fibers in a twisted yarn, only a component of the fiber tenacity is utilized when the yarn is stretched longitudinally. Twist and yarn diameter, i.e., the distances of the fibers from the yarn axis, are the determining factors of the helix angle. Increasing twist and yarn diameter produce higher

helix angles and, therefore, cause a decrease of the effective stress component and reduction of the tensile strength. This effect is independent of the shape of the stress-strain curve of the fiber material; in other words, the component effect is the same for fibers of high or low modulus provided the yarn geometry is the same.

(b) Serigraph Effect - The elongation of the individual fibers at a given yarn elongation varies with their helix angle. The elongation of fibers or fiber portions with the lowest helix angle (located in the core of the yarn) is approximately equal to the yarn elongation while fibers which are inclined toward the yarn axis are strained to a lesser degree. Due to this difference in the strain level of the individual fibers the stresses effective on the yarn are distributed unevenly upon the fibers. Those located in the center of the yarn have to carry more load and reach the breaking point sooner than those in the periphery of the yarn. In fibers with a low modulus this effect is not as evident as those with a high modulus, and for this reason the latter are highly sensitive to twisting.

(c) Yarn Evenness Effect - In the case of spun yarn the actual number of fibers per cross section and their twist change along the yarn due to the imperfections of the spinning process. Therefore, the behavior of the yarn as resulting from the component and serigraph effect will also change according to the distribution pattern of fibers per cross section and helix angles which can both be treated statistically.

Variations in the packing density of the fibers resulting from fiber crimp, fiber stiffness, cross-sectional shape and spinning conditions have an effect on the yarn behavior in addition to the fiber properties and basic construction of the yarn as described by count and twist. The calculation of the yarn behavior on the basis of the three effects mentioned above will not be affected by such variations if consideration is given to the variation of the helix angle resulting from fiber crimp and packing density. On this basis it is possible to predict with good reliability the following yarn properties: breaking strength and elongation of yarns, take-up in twisting, resistance to and recovery from stretching.

While a great number of studies have been carried out on the tensile elastic behavior of yarns and fabrics, very little theoretical and experimental information is available on the compressional elastic properties. In the actual use of fabrics, however, yarns are as often exposed to compression as to stretching,

or even move. Especially such characteristics as hand and drape, wrinkle resistance, warmth, and wear resistance appear to be affected by compressional elastic behavior as well as by tensile elastic behavior. Basically, the two are interrelated, and the approach taken by Hamburger and Platt will also be applicable for determining compressional behavior. Factors which have a detrimental effect on the tensile properties, such as low packing density of the fibers and high helix angle, will contribute favorably to the compressional characteristics. This conflicting behavior has not been given enough consideration in the past, particularly with the man-made fibers. In using the natural fibers, cotton and wool, the fiber shape to a certain extent automatically took care of the compressional elastic behavior. In addition, the trade had learned by trial and error that a yarn twist lower than that which secures maximum strength is not only more economical, but may also secure yarns of better end-use performance. In most of the yarns spun from man-made fibers the compressional characteristics have been neglected in favor of the tensile properties. To improve the yarns compression-wise we first must learn that maximum tensile strength is not necessarily what we are looking for. In addition, the manufacturing of permanently crimped fibers and the selection of proper yarn twists will help to improve the compressional elastic behavior of yarns.

#### 7. END-USE DEMANDS ON FIBER PROPERTIES

To conclude and summarize the discussion on the interrelationship of fiber properties, form factors, and fabric performance we will now attempt to tie the end-use requirements to the fiber properties, using as an example an important group of apparel fabrics, namely suitings and outerwear fabrics. In Table VIII individual fabric characteristics, which were classified in Table III, are related to the various consumer requirements for this fabric group, and test methods applicable for evaluating these performance characteristics are given. Further, a priority rating is assigned to each characteristic, Priority 1 indicating that maximum performance with regard to the particular characteristics demanded, Priority 2 meaning that certain minimum requirements must positively be met, Priority 3 applying to characteristics of secondary importance, and Priority 4 applying to those of minor importance.

Aesthetic Appeal - Appearance and retention of appearance with regard to color is strictly a matter of the inherent fiber characteristics and dye methods. In addition to the ease of dyeing and the colorfastness, it is desirable that a fiber material permit both union and cross dyeing when blended with some of the major fibers used in this field such as acetate, viscose and wool.

TABLE VIII

END-USE REQUIREMENTS AND RELATED PROPERTIES  
OF SUITING AND OUTERWEAR FABRICS

<u>Requirement</u>	<u>Related Fabric Characteristic</u>	<u>Applicable Test Methods</u>	<u>Priority</u>
AESTHETIC APPEAL	Appearance	a) Subjective (visual) evaluation b) Physical (spectrometric reflectance) tests	1
	Retention of Appearance	a) Subjective evaluation b) Fastness tests	2
	Hand & Drape Softness Resilience Touch Flexibility Drape	a) Subjective evaluation b) Laboratory tests such as: Compressional and tensile elastic behavior (stress-strain-time relationship) Flexibility tests Friction tests Drapemeter tests	1-2
TAILORING QUALITY	Form stability in Tailoring Sponging Pressing Changing RH	a) Tailoring test b) Laboratory tests such as shrinkage in: Sponging Pressing Ironing Changing RH	1-2
	Resistance to fraying & yarn slippage	Fraying test Yarn slippage test	2
	Sewability	Sewability test including: Yarn severance Needle hole fusion Needle hole retention Seam efficiency	2
PHYSIOLOGICAL REQUIREMENTS	Comfort Weight Touch Drapeability Warmth or Coolness Static Electricity	Weight Laboratory tests as for hand and drape Heat transmission Air and water vapor permeability Absorption Heat of absorption Rate of drying Wicking Static tests	1-2

TABLE VIII (Cont.)

END-USE REQUIREMENTS AND RELATED PROPERTIES  
OF SUITING AND OUTERWEAR FABRICS

<u>Requirement</u>	<u>Related Fabric Characteristic</u>	<u>Applicable Test Methods</u>	<u>Priority</u>
PROTECTIVE REQUIREMENTS	Water Resistance	Static and dynamic absorption tests, rain penetration tests	3-4
	Fire Resistance	Flame resistant test Rate of burning test Cigarette test	3-4
DIMENSIONAL STABILITY	Resistance to shrinkage in Sponging	Shrinkage tests using washing machine, tumbler dryer, U. S. Hoffman press, special air chamber	2
	Wet-dry cleaning		1-2
	Laundering		2
	Pressing and ironing		1-2
	Changing RH		1-2
	Resistance to wrinkling	a) Wear tests	1
	Retention of creases	b) Lab. wrinkle tests	1
		c) Crease Angle tests	1
	Resistance to and recovery from: stretching and compression	a) Wear tests b) Tensile and compressional tests	1-2
WEAR RESISTANCE	Effect of wear on appearance	a) Wear tests b) Abrasion tests to duplicate shine, crocking, pilling, threadbareness	2
	Breakdown of fabric structure by gradual wear	a) Wear tests b) Flex and surface abrasion tests	2
	Tearing	Tearing strength test	2-3
	Snagging	Snag resistance	2-3

Luster, another factor in appearance, can be varied in all man-made fibers in a wide range both by delustering of the fiber material and by a proper selection of fiber fineness and shape, or a combination of these. In addition, yarn twist, crimp, weave, and cover factor may have a significant bearing on fabric luster.

The hand and drape of fabrics are largely determined by their tensile and compressional elastic behavior. The mechanism of these properties has already been discussed. The inherent tensile elastic behavior of the fiber; fiber, yarn, and fabric geometry; as well as the interfiber friction contribute to the tensile and compressional properties. Experimental evidence indicates that textile fibers whose initial stiffness is high, whose stiffness decreases as the deformation exceeds four to five per cent (approximately 1 to 1.5 g/den) and whose immediate elastic recovery is high in the low and medium stress-strain range secure not only good hand and drape characteristics, but also the resilience and wrinkle resistance desirable in apparel fabrics in general. However, the inherent characteristics alone are not sufficient to produce optimum fabric performance with regard to the characteristics under discussion. A permanent helical type fiber crimp can help considerably in meeting the softness, resilience and flexibility requirements and can also contribute to crease resistance, warmth and wear resistance.

Tailoring Quality - So far as the individual fiber is concerned the characteristics determining the tailoring quality such as the form stability, sewability, and resistance to fraying and yarn slippage are: medium to high elastic modulus in the low stress-strain range, low or medium absorbency and swelling characteristics, and a medium to low regain (or at least the fiber should not change its dimensions significantly when passing from one moisture content to another). Wet and dry heat as exerted in sponging, pressing, and ironing should not plasticize the fiber material, nor should it cause swelling or shrinkage. The melting point of the fiber and its frictional characteristics against metal must be such that sewing does not cause needle hole fusion and yarn severance. Depending on the surface preparation of the fiber, the tightness of the weave, the needle type and sewing speed, a softening or melting point higher than 250 C will prevent needle hole fusion. In some cases fibers with as low a melting point as 200 C. can secure satisfactory sewability even under conditions which produce maximum heat. A low packing density of the fibers within the yarn as created by proper crimp and yarn constructions will also help to improve this characteristic.

Physiological Requirements - Comfort is still one of the most obscure characteristics of textile fabrics, at least when we try to express it in terms of definite physical and chemical characteristics. However, so far as the weight, touch, drapeability and static electricity are concerned, which all contribute to comfort, enough knowledge is available on the requirements. With regard to properties of the individual fiber it is desirable to have fibers with a relatively low specific gravity which secure maximum coverage. The demands on the fiber from the drapeability standpoint have been discussed above. The touch puts certain limitations on the modulus (not too stiff, not too low) as well as on the fiber denier, but it is largely determined by the yarn and fabric geometry which contribute to the surface contour of the fabrics, and by the finish which may change the interfiber friction as well as the wicking characteristics. The cross-sectional shape as outlined under hand and drape, i.e., the tendency of flat cross sections to pack together, also enters into the picture. Hygroscopic fibers do not present any problems so far as the static electricity is concerned. In hydrophobic fibers this problem may be overcome by anti-static agents. However, it must be considered that some of these agents may conflict with the hand and drape requirements as well as those required to prevent water penetration and excessive wicking. The most important fabric property contributing to warmth is thickness that is not lost during wearing. Fibers with a low specific gravity, high initial modulus and elastic recovery both dry and wet, and a permanent crimp contribute most to fabric thickness. It is not yet clearly known what effect a low, medium, or high regain has on warmth and coolness. However, excessive wicking resulting from a highly wettable fiber surface, which can be present both on hydrophylic and hydrophobic fibers, appears to be undesirable for comfort. For coolness the most decisive factor is minimum fabric thickness. In order to be able to produce thin fabrics a fiber material must be sufficiently tough in addition to the other requirements outlined before. It must also secure sufficient coverage in thin fabric and should not be translucent. For water impermeable fabrics staple fibers with a moderate amount of swelling and absorbency appear to be the most practical. They will secure, under dry and wet conditions, the required tightness and still retain some water vapor permeability. In order to obtain water repellency the surface of the individual fibers should be hydrophobic. This will also help to resist soilage produced by the hydrophylic components of natural soil.

Dimensional Stability - The most important fiber properties contributing to shrink resistance are minimum swelling in water and cleansing agents, resistance to fibrillation by wet abrasion, and dimensional stability of the individual fiber at temperatures up to 150 C. For wrinkle resistance, in addition to the properties

already mentioned under hand and drape, the fiber material should be preferably of low regain and absorbency. A round cross-sectional shape also appears to be of advantage. Coarse fibers tend to resist wrinkling better than fine fibers, while fine fibers recover more easily from wrinkling than coarse ones. Permanent fiber crimp can contribute considerably to wrinkle resistance since it helps to lower the stress and strain level effective upon the individual fibers. For crease retention the most important fiber properties are adaptability to heat setting and minimum regain and absorbency.

Wear Resistance - In order to resist the complex mechanical wear actions which cause fiber breakdown in yarn and fabric structures, the following fiber characteristics appear to be most desirable: high elastic energy absorption, dry and wet (product of strength and elastic elongation and shape factor); high absolute and relative knot and loop strength.

For given strength properties, fine fibers from 1 to 2 denier have a lower overall wear resistance than those in a range of 3 to 5 denier.

Fabrics made wholly or in part of extremely tough fibers (maximum elastic energy absorption) have a tendency towards pilling. However, by changing the geometric form of the fibers, yarns and fabric (high crimp, medium-to-high twist, short floats) this deficiency may be overcome.

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The foregoing brief analysis of the end-use requirements of textiles and the interactions of fiber, yarn, and fabric properties has attempted to show in broad perspective a problem usually discussed from a more limited viewpoint. Its purpose is to discourage the oversimplification often implied in studies of basic fiber properties that fail to take into consideration the translation of these properties as the fiber is converted into a yarn and then into a fabric; or in studies which overemphasize fabric and end-item evaluation without giving sufficient attention to the basic causes of the behavior noted and the multitude of performance characteristics required. The fiber scientist and textile technologist should be aware of the complexity of the overall problem facing him in the development of improved fibers, yarns, and fabrics.

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